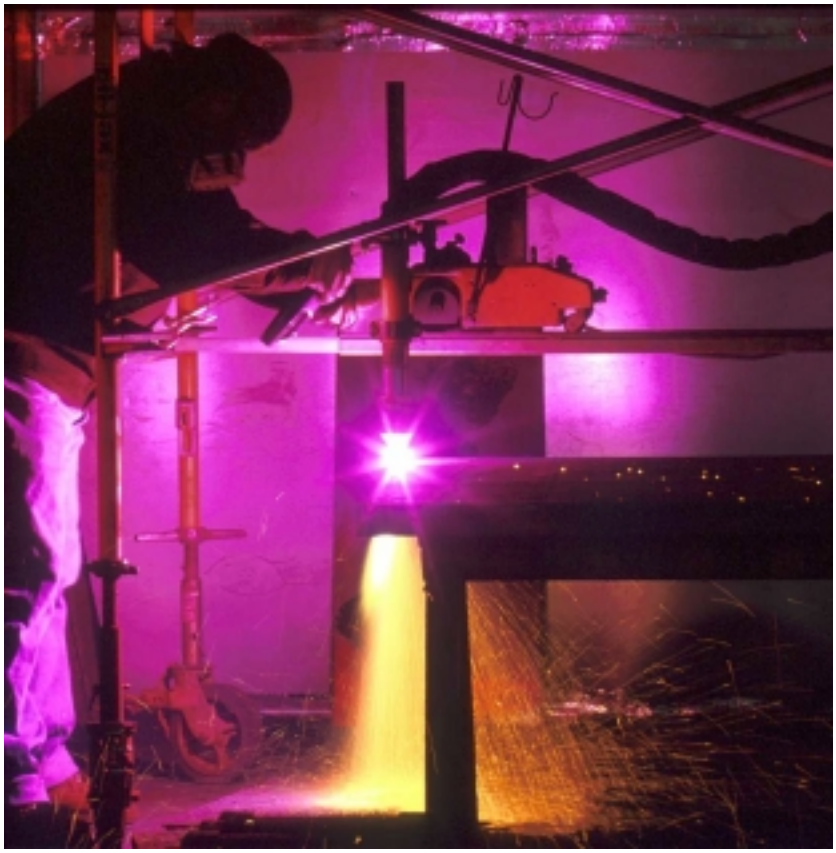
Assessment of Air Emissions from Shipyard Cutting Processes



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Abstract

Open air metal cutting processes that are used in Navy and commercial shipbuilding, ship repair, and ship scrapping operations produce air emissions. Increasingly stringent regulatory requirements (both OSHA and EPA) and a lack of published cutting emission factors are making it difficult to quantify the emissions associated with these processes. This paper presents the results of recent research directed at the characterization of emissions from Shipyard cutting operations. In particular, emissions were sampled for an oxy-MAPP cutting process and a reduced emission Argon-Hydrogen Plasma Arc (AHPA) cutting process.

Sampling of the oxy-MAPP cutting process was conducted at Puget Sound Naval Shipyard (PSNS) using the same cutting procedures that are employed in the scrapping of thick steel sections of U.S. Navy submarines. AHPA cutting emissions were characterized at Battelle (Columbus, OH) using steel base plate and some submarine hull sections from PSNS. For both experiments, a test enclosure was constructed along with the necessary ducting and sampling ports. Most of the sampling was conducted on thick (≥ 2 inches) high strength steel plate. Sample surface conditions varied from blasted bright metal to coated surfaces with adhesive residue. Emissions were monitored in accordance with EPA source test procedures. Measurements included metals content, hexavalent chromium, total particulate, and particle size distribution. Particle size distribution was determined using a real-time particle analyzer that uses a cascade impactor with a quartz crystal microbalance. Metal analysis was done using EPA's modified SW846 method and included quantitative determination of antimony, arsenic, beryllium, cadmium, cobalt, chromium (total), copper, iron, manganese, molybdenum, nickel, lead, vanadium, and zinc. OSHA's Method 215 was used to analyze hexavalent chromium using ion chromatography.

Emission factors are presented for both oxy-MAPP cutting and AHPA cutting of thick, high strength steel plates. Also, limitations of the experimental and analytical procedures are documented. The emission factors presented in this paper can be used by many industries to quantify the emissions associated with cutting thick steel plates.

Introduction

Thermal metal cutting operations make up a large part of the industrial activity associated with ship construction, ship repair, and ship scrapping operations. These cutting operations can create a multitude of health and safety issues, including worker and environmental exposure. The primary concern is the cutting fume that results from burning through the structural materials used in ships. The characteristics of this fume are dependent on the material being cut, the cutting process and parameters, and the presence of coatings or contaminants in the vicinity of the cutting area. The primary contaminants that result from cutting typical ship steels include particulate matter, heavy metals, metal ions, oxides of nitrogen, carbon monoxide, and ozone. Depending on the surface characteristics (paints, adhesive residue, tile residue, petroleum products, or other contaminants), emission of organic compounds can also occur.

This paper presents the results of air sampling that was conducted for oxy-MAPP® (MAPP is the trademark for a liquified acetylene compound) cutting, arc-gouging, and argon-hydrogen plasma arc (AHPA) cutting. The oxy-MAPP (and arc-gouging) emissions were sampled at Puget Sound Naval Shipyard (PSNS) while the AHPA emissions were measured at Battelle's West Jefferson facility in Columbus, OH. Emissions of particulate matter, metals, and metal ions are compared for the three processes.

Materials and Methods

Cutting Process and Test Pieces

For the characterization of the oxy-MAPP cutting fume at PSNS a total of 17 tests were conducted. Test segments consisted of 5 X 8 ft sections of submarine pressure hull (HY-80 steel) or tank plate structure (carbon steel). Pieces were tested with varying combinations of interior, exterior, and no coatings. Total test time of approximately 15 minutes was used for each segment (actual arc time was 7 ½ minutes since the test burns were repeated in 30 second on and off cycles). Pressures at the gas regulators were set at 70 – 120 psi for oxygen and 10 – 15 psi for MAPP gas. The torch tip used was Victor type CSM-X size eight.

The characterization of the argon-hydrogen plasma arc cutting process was accomplished by conducting a series of 26 test burns. The test pieces included 2-in thick HY80 steel base plate with the mill primer, and 2-in thick HY80 submarine pressure hull sections with interior and exterior coatings. Sample cuts were made continuously with arc times varying from 1 to 3.25 minutes. The movement of the torch was automated and preset cutting speeds from 12-in/min to 27-in/min were employed. The cutting amperage was varied from 360 to 600 amps. The plasma arc cutting system included ESAB ESP600C 600 amp power supply with a PT-19XLS plasma cutting torch.

Test Chamber

Separate test enclosures were constructed for the sampling at PSNS and for the sampling at Battelle. These enclosures were 10 ft wide and 16 ft long. They differed in that the enclosure at PSNS was 8 ft high while the enclosure at Battelle had an extra 2 ft of height to allow for easy fork lift access. The walls and roof of the test enclosure were framed

with metal studs and covered on the interior with 20 gage galvanized steel. One end of the test chamber was covered with a removable fire retardant curtain that allowed worker entry as well as movement of work pieces. Air was pulled through small gaps around the fire retardant curtain, over the work area, and through the exhaust duct. Sample ports were made in the exhaust duct to facilitate sample collection. The exhaust blower was located at a point 20 ft from the exhaust duct inlet. Figure 1 illustrates the test chamber, exhaust duct, and the relative positions of the burner and the work piece. A photograph of the test chamber and sampling duct at Battelle is shown in Figure 2.

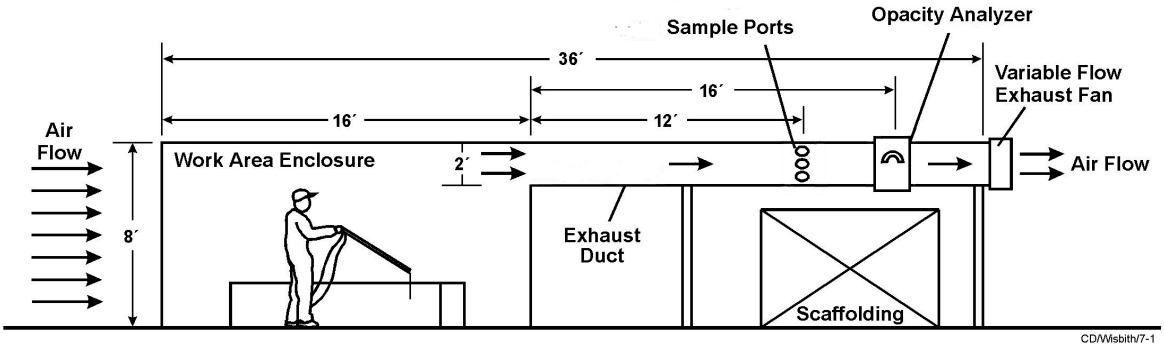

Figure 1: Test Configuration for Sampling Cutting Emissions

Sampling Plan

The sampling of emissions associated with oxy-MAPP cutting and arc-gouging at PSNS is described in Table 1, and the sampling of Ar-H plasma arc cutting at Battelle is described in Table 2. The arrangement of the test plate and the AHPA cutting torch is shown in Figure 3. The speed of the cutting torch was preset and remained constant through each test. Once cutting was initiated, air samples were collected from the exhaust duct using 37-mm diameter filters under isokinetic flow conditions. The filters were analyzed for total particulate matter and the following metals: antimony (Sb), beryllium (Be), cadmium (Cd), cobalt (Co), chromium (Cr), hexavalent chromium (Cr(VI)), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), nickel (Ni), lead (Pb), vanadium (V), and zinc (Zn). In addition, filters from the PSNS tests were analyzed for arsenic (As). Finally, the particle size distribution was analyzed during four of the PSNS tests and five of the Battelle tests.

Velocity Traverse

The air velocity across the cross section of the exhaust duct was measured using a portable anemometer. Readings were taken at 12 different grid points in the duct at the beginning and the end of each test day. These readings were evaluated to determine the uniformity of the air flow in the duct and the average velocity of the exhaust air at the sampling port.

Figure 2: Air Emission Sampling Facility at Battelle

Sample Collection
Air samples were collected using 37-mm diameter filter cartridges for determination of total particulate concentration and subsequent metals analyses. The configuration of the sampling probe is shown in Figure 4. Cellulose-ester matched weight (MCE) filters with 0.8 micron pore size were used for the total particulate and metals sampling. Air samples for hexavalent chromium analysis were collected using 37-mm diameter, 5.0 micron pore size, polyvinyl chloride (PVC) filters. Matched weight refers to 2 filters that are matched in weight and loaded into a cassette in a controlled lab environment of 20 Deg. Celsius and 50% relative humidity. The top filter collects particulate matter and the bottom filter serves as a control. After sampling, both filters are removed and weighed; the difference is the weight of the particulate matter collected. The volume of air sampled, temperature, humidity and other sampling information was documented on the particulate field data sheets.

Figure 3: Test Arrangement for AHPA Cutting

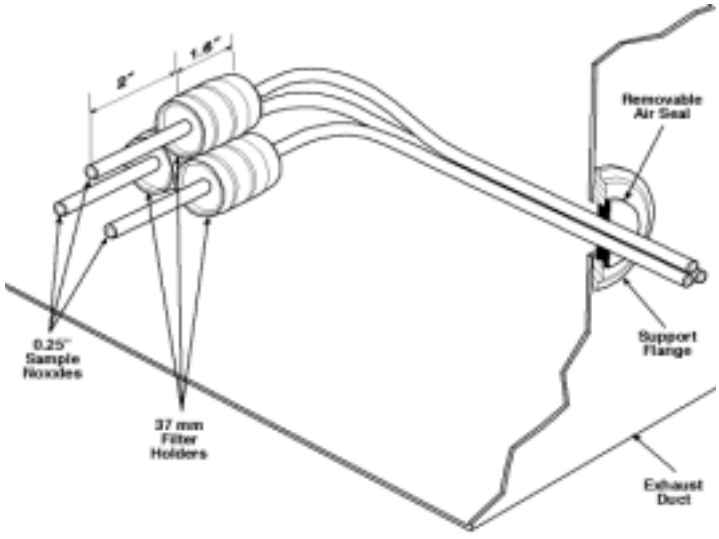

Figure 4: Configuration of Sampling Probe and Filter Cartridges

Particle Size Distribution
Particle size distributions associated with selected test burns were measured using a real time particle size analyzer (Model PC-2) manufactured by California Measurement, Inc. The system consisted of a quartz crystal microbalance cascade impactor. Quartz crystal sensors were used in each stage as mass monitors to provide real time mass collection information. A photograph of the cascade impactor with its probe extending into the test section is shown in Figure 5.

Metal Analyses
The MCE and PVC matched weight filters for each sample were removed from their cassettes and weighed on a Metler-Toledo Model AT20 microbalance. The difference in weight between the two matched filters was used to determine the actual weight of particles collected. The first MCE filter was analyzed for all the metals previously listed with the exception of Cr (IV). Samples were extracted and digested using concentrated nitric acid. Sample extracts were then analyzed using inductively coupled plasma mass spectrometry (ICP-MS). The ICP – MS instrument was calibrated using a blank and five calibration standards prepared from NIST traceable standards.

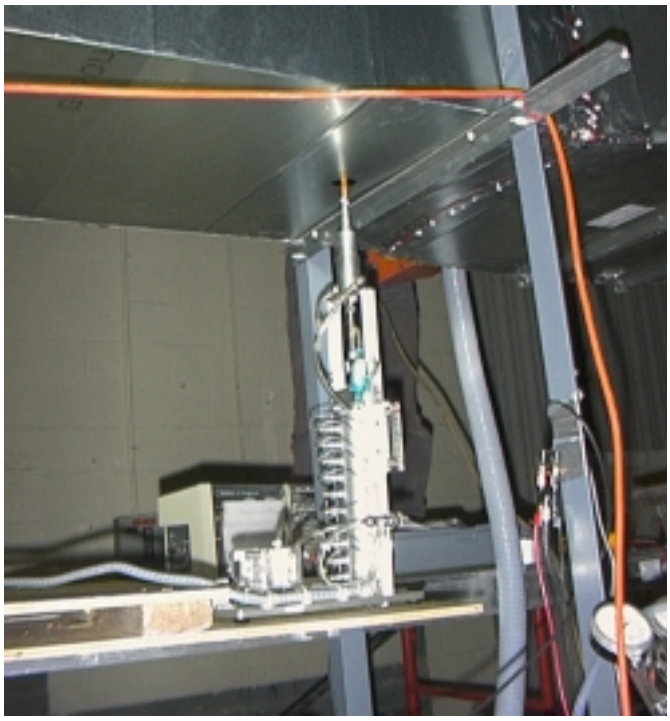

Figure 5: Cascade Impactor for Determining Particle Size Distribution

OSHA Method 215 was used to analyze the PVC filters for hexavalent chromium. Samples were extracted using an aqueous solution containing 10% Na_2CO_3, 2% $NaHCO_3$, and a mixture of phosphate buffer and magnesium sulfate. After dilution, an aliquot of this solution was analyzed for Cr(VI) by an ion chromatograph equipped with a UV-vis detector at the 540-nm wavelength.

Results and Discussion

Tables 3 and 4 present emission factors for total particulate matter (TPM), hexavalent chromium, and metals as determined from the sampling at PSNS and Battelle, respectively. All emission factors are presented in terms of mass of pollutant emitted per kilogram of cut material. The volume of cut material is equal to the cut length times the plate thickness times the average kerf of the cut.

Pollutant mass was calculated from the source test data. In the case of TPM, the mass of TPM was determined from the initial and final weights of filters. For metals and Cr(VI), masses were determined from corresponding analytical results. Cut length, average kerf, time required for cutting, and plate thickness are presented in Tables 1 and Table 2, and were used in conjunction with the pollutant mass data to generate emission factors.

The total particulate emission factor for oxy-MAPP cutting of HY-80 steel without coatings varied from 14.2 to 18.5 g/Kg with an average value of 15.2 g/Kg. Total particulate emission factors for coated HY-80 varied from 10.2 to 52.2 g/Kg with an average of 26.8 g/Kg. The wider range in emissions for the coated samples is due to variations in type of coating, whether one or both surfaces were coated, and the plate thickness which varied from 1-in to 2.93-in on the coated samples. Arc-gouging resulted in much higher particulate emissions than oxy-MAPP cutting (47.1 to 61.9 g/Kg vs 14.2 to 18.5 g/Kg for uncoated HY-80, respectively).

A comparison of total particulate emission factors by cutting process is presented in Figure 6. The emission factors shown in this figure are averages for the data shown in Tables 3 and 4 with the following restrictions. Since there does appear to be a thickness effect, the data for these averages were limited to plate thicknesses of 2-in ± ½ in. The 600 amp AHPA data were limited to the runs with cutting speeds greater than 24 in/min, while the 500A and 360A AHPA data correspond to cutting speeds of about 13 in/min. For cutting methods which had eight or more data points (oxy-MAPP and 600 amp AHPA) the high and low emission factors were omitted and the remaining data points were averaged. The 500 amp and 360 amp AHPA cutting cases each had only four data points, therefore all four points were used to calculate the average. As shown in this figure arc-gouging produces significantly more emissions than the cutting processes when compared on the basis of material removed. It is also clear that the AHPA process can reduce emissions substantially relative to oxy-MAPP cutting, if the amperage is chosen appropriately for the plate thickness. Emission factors for the 600 amp AHPA process were comparable to the oxy-MAPP process. The 500 amp AHPA process resulted in about ¼ the oxy-MAPP emissions, and the 360 amp AHPA process resulted in emissions that were an order of magnitude less than the oxy-MAPP emissions.

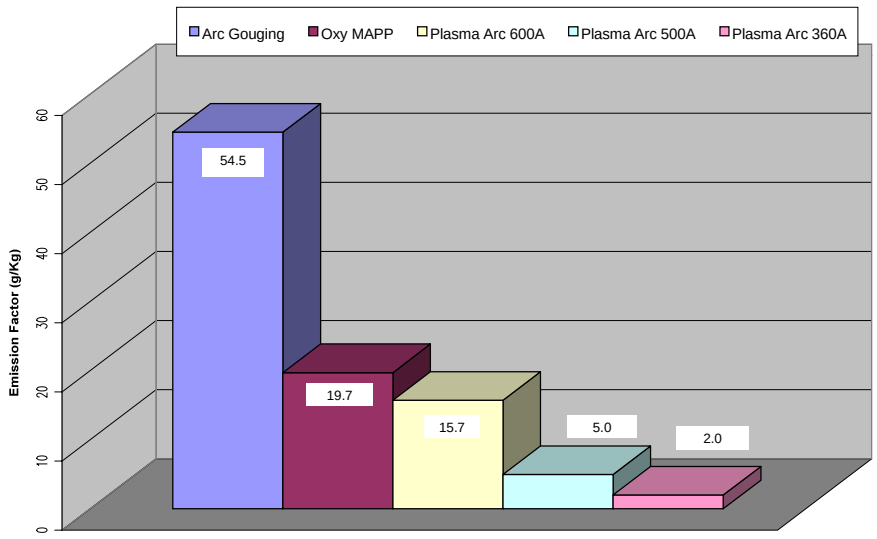

Figure 6: Comparison of Total Particulate Emission Factors by Process

There was substantial variation in the analytical results reported by two different labs for hexavalent chromium for the tests performed at PSNS. This variation occurred even though samples were taken side by side and both labs (Navy and Battelle) used the same analytical method (OSHA method 215). For oxy-MAPP cutting on HY-80, 13 samples were analyzed by each laboratory with Cr(VI) varying from not detectable up to 3.96 mg/Kg. Ninety two percent of the Cr(VI) analyses indicated values of 1.05 mg/Kg or less. (The remaining two data points, 2.14 and 3.96 mg/Kg, deviate significantly.) It was clear, however, that the arc-gouging process (samples 13 and 15) generated significantly more Cr(VI) when compared to oxy-MAPP cutting (samples 11, 12X and 21). A comparison of average Cr(VI) emission factors for each cutting process is presented in Figure 7. From this chart it can be seen that more than an order of magnitude reduction in Cr(VI) can be achieved by going from an oxy-MAPP cutting process to a 360 amp argon-hydrogen plasma arc cutting process.

The average emission factors for a typical metal, in this case nickel, are displayed in Figure 8. The pattern is again very similar to that presented for total particulate and for Cr(VI). Arc-gouging produces by far the most nickel emissions. Emissions from the 360 amp AHPA process are again an order of magnitude less than the oxy-MAPP emissions.

Generally, the magnitude of the emission factors (excluding the carbon steel samples, 16 and 17 in the PSNS sampling) is consistent with the HY-80 chemistry, that is iron, nickel, and chromium in decreasing order. The oxy-MAPP emission factors for molybdenum, however, are consistently greater than the factors for chromium in spite of the fact that there is significantly more chromium than molybdenum in HY-80. For AHPA cutting the chromium emissions are consistently greater than the molybdenum emissions.

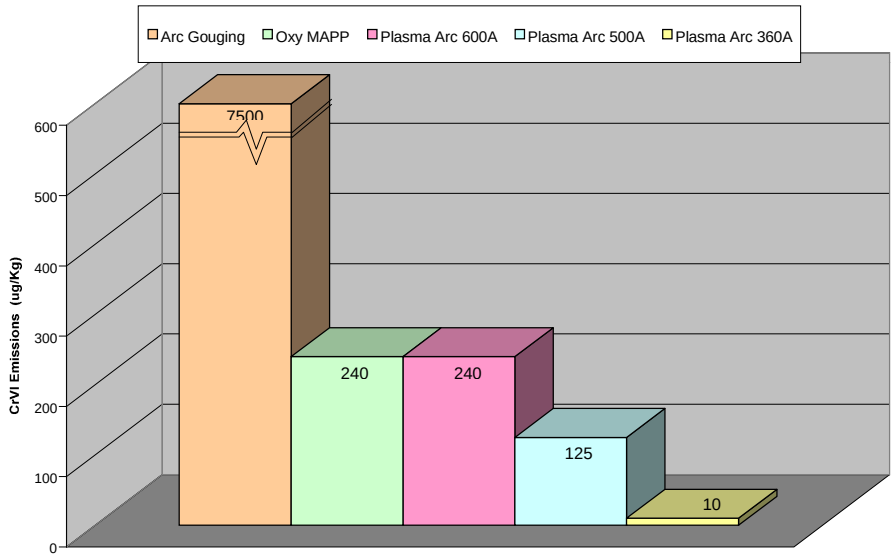

Figure 7: Comparison of Cr(VI) Emissions by Cutting Process

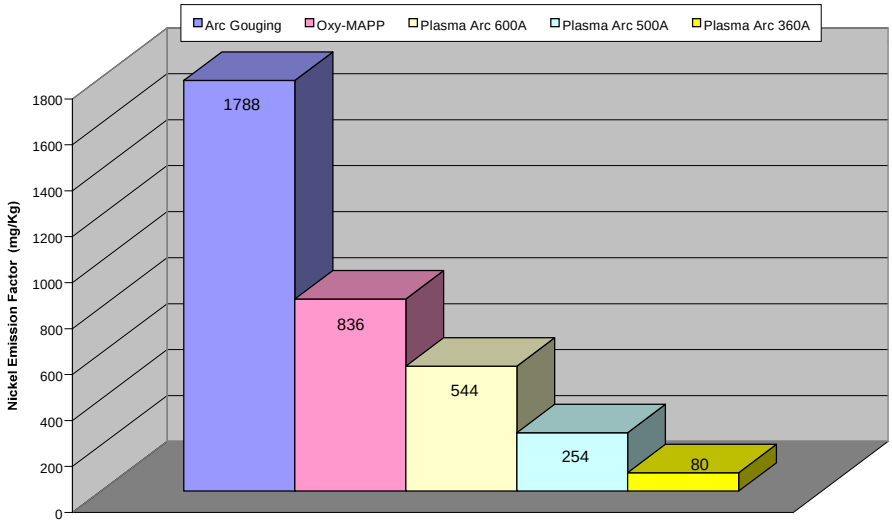

Figure 8: Comparison of Nickel Emissions by Cutting Process

Table 5 presents the size distribution of the cutting fumes, which range from less than 0.05 to 25 micron. This table provides cumulative mass fractions corresponding to each particle size. Difference between the two consecutive cumulative values provides size fractions in each size class. Figure 9 illustrates the size distribution for oxy-MAPP cutting based on four samples analyzed at PSNS. The distribution is presented in a semi-log graph in order to improve the readability of the cumulative mass fractions. It can be

noted that the PM_{10} fractions for these samples range from 0.91 to 1.00 indicating that 91% to 100% of the mass is 10 microns or smaller. Similarly, $PM_{2.5}$ data indicate that 70% to 93% of the mass is less than 2.5 microns. These percentage values can be used in conjunction with TPM emission factors to estimate the emission factors for PM_{10} and $PM_{2.5}$. However, due caution should be exercised as the data are based on a limited number of samples. Similarly, Figure 10 illustrates the size distribution of the AHPA emissions based on five cascade impactor samples during the cutting at Battelle. About 82 to 98% of particulate mass is below 10 micron size, and 37 to 64% of particulate mass is below 2.5 micron in size. By superimposing the the two sets of data it can be observed that the particles associated with oxy-MAPP cutting are generally a little smaller than the particles associated with AHPA cutting ($PM_{2.5}$ for oxy-MAPP cutting is greater than $PM_{2.5}$ for AHPA cutting).

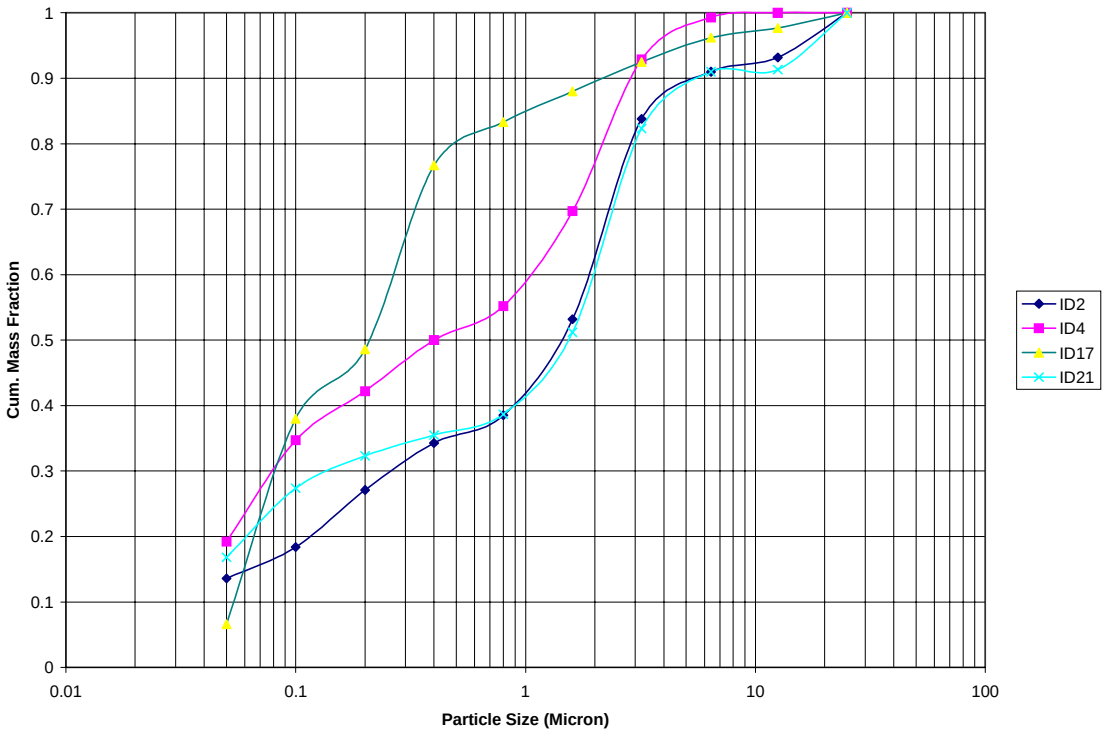

Figure 9: Particle Size Distribution for Oxy-MAPP Cutting

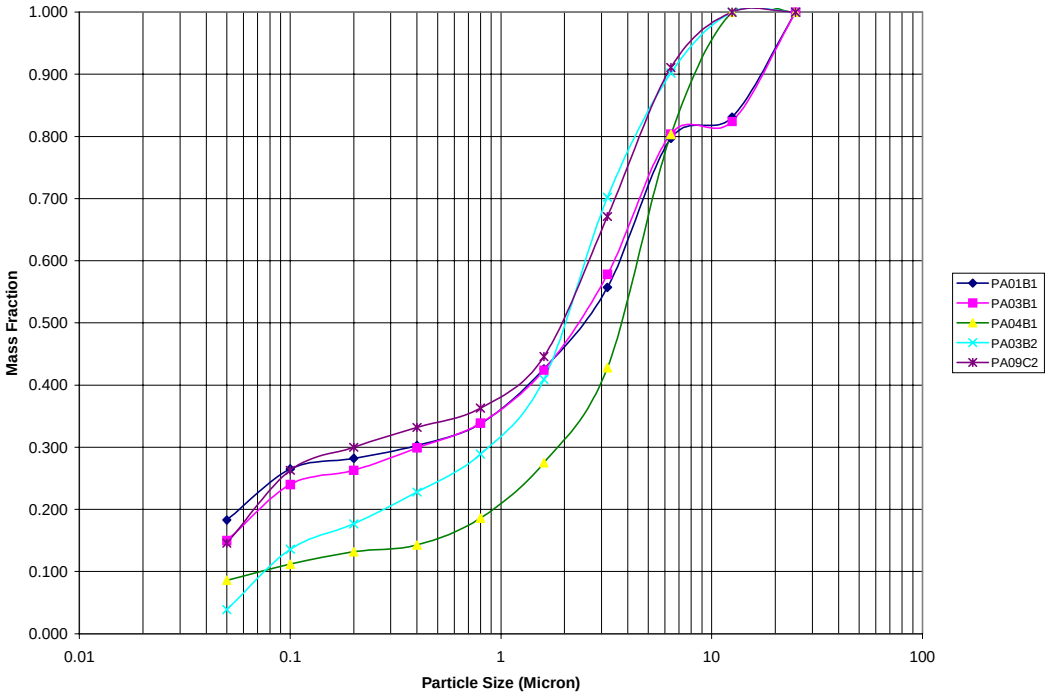

Figure 10: Particle Size Distribution for AHPA Cutting

Conclusions

Emission factors are presented for total particulate matter, metals, and hexavalent chromium based on field measurement of cutting emissions at the Puget Sound Naval Shipyard and Battelle Labs. Processes observed include arc-gouging, oxy-MAPP cutting, and argon-hydrogen plasma arc cutting. Test burns in a controlled chamber were conducted on submarine structural steels with and without interior and exterior coatings. Emissions factors were calculated and should be helpful in quantifying cutting emissions for TPM, metals, Cr(VI), PM_{10}, and $PM_{2.5}$. The following conclusions are drawn from the experimental observations.

Arc-gouging has much higher emission factors than any of the cutting processes evaluated. Emission factors for Cr(VI) were 30 times greater than any of the cutting processes.

A 360 amp argon-hydrogen plasma arc process can reduce TPM, Cr(VI), and metal emissions by an order of magnitude relative to an oxy-MAPP cutting process.

A greater percentage of fine particles was noted for oxy-MAPP cutting relative to the argon-hydrogen plasma arc process. The cumulative mass fraction of $PM_{2.5}$ for 360 amp AHPA cutting was ½ that of oxy-MAPP cutting process.

Additional sampling has recently been completed using a ten-stage in-stack cascade impactor. These data are currently being analyzed and will provide information on chemical speciation within different particle size bands.

References

1. 40 CFR 60 – Standards of Performance for New Stationary Sources Appendix A. Test methods, Method 1 – Sample and Velocity Traverses for Stationary Sources.

2. 40 CFR 60 – Appendix B – Performance Specifications Performance Specification 1 – Specifications and Test Procedures for Opacity Continuous Emission Monitoring Systems in Stationary Sources.

3. 40 CFR 60 – Standards of Performance for New Stationary Sources, Appendix A, Test Method 9 – Visual Determination of the Opacity of Emissions from Stationary Sources.

4. EPA SW846 Method 6000 Series, U.S. Department of Health and Human Services, National Institute of Occupational Safety and Health (NIOSH)

5. NIOSH Manual of Analytical Methods, Method 7604 Chromium Hexavalent.

6. 40 CFR 60 – Standards of Performance for New Stationary Sources, Appendix A, Test Methods, Method 5 – Determination of Particulate Emissions from Stationary Sources.

Note: 40 CFR refers to the Code of Federal Regulations, Chapter 40, Protection of Environment, U.S. Environment Protection Agency.

Table 1: Test Matrix for PSNS Sampling

ID	Section Cut	Alloy	Inside Coating	Outside Coating	Cutting Method	Thickness (in) *	Cut Length (in)	Ave. Kerf (in)	Cut Vol. (in^3)	Burn Time (min)	Measured Parameters			
											TPM	M	Cr(VI)	PSD
11	PH	HY-80	Blasted	Blasted	Oxy-MAPP	2.11	135	0.43	122.5	7.77	X	X	X	
**12	PH	HY-80	Blasted	Blasted	Oxy-MAPP	2.23	234	0.38	198.3	15.08	X	X	X	
12x	PH	HY-80	Blasted	Blasted	Oxy-MAPP	2.23	119	0.38	100.8	7.45	X	X	X	
21	PH	HY-80	Blasted	Blasted	Oxy-MAPP	2.11	122	0.5	128.7	7.57	X	X	X	X
1	PH	HY-80	Paint	Adhesive/Tile Residue	Oxy-MAPP	1.58	143	0.38	85.86	7.63	X	X	X	
2	PH	HY-80	Paint	Adhesive/Tile Residue	Oxy-MAPP	1.58	195	0.38	117.1	7.28	X	X	X	X
3	PH	HY-80	Paint	Anti-fouling Paint	Oxy-MAPP	1.6	124	0.38	75.39	7.83	X	X	X	
4	PH	HY-80	Paint	Anti-fouling Paint	Oxy-MAPP	1.6	217	0.38	131.9	7.58	X	X	X	X
5	PH	HY-80	Paint	Blasted	Oxy-MAPP	1	214	0.38	81.32	7.67	X	X	X	
6	PH	HY-80	Paint	Blasted	Oxy-MAPP	1	207	0.38	78.66	7.75	X	X	X	
7	PH	HY-80	Blasted	Adhesive/Tile Residue	Oxy-MAPP	2.13	124	0.5	132.1	7.42	X	X	X	
9	PH	HY-80	Blasted	Anti-fouling Paint	Oxy-MAPP	2.93	108	0.38	120.2	7.58	X	X	X	
10	PH	HY-80	Blasted	Anti-fouling Paint	Oxy-MAPP	2.7	109	0.38	111.8	7.73	X	X	X	
16	TP	CS	SHT	Graphite/Adhesive Residue	Oxy-MAPP	0.49	217	0.5	53.17	7.67	X	X	X	
17	TP	CS	AF Paint	Graphite/Adhesive Residue	Oxy-MAPP	0.43	298	0.62	79.45	7.83	X	X	X	X
13	PH	HY-80	Blasted	Blasted	Arc-gouging	0.38	192	0.42	30.64	7.67	X	X	X	
15	PH	HY-80	Blasted	Blasted	Arc-gouging	0.38	60	0.56	12.77	7.57	X	X	X	

PH - Pressue Hull; TP - Tank Plate; CS - Carbon Steel/Graphite Tile; TPM - Total Particulate Matter
M - Metals; Cr(VI) - Hexavalent Chromium; PSD - Particle Size Distribution
** For the oxy-mapp cuttingall cuts were through the plate thickness, for arc-gouging the gouge depth is shown*
*** Flow variations occurred during this test*

Table 2: Test Matrix for Sampling at Battelle

Seq. No.	Sample ID	Base Plate	Cutting Method	Cut Length (in)	Average Kerf (in)	Cut Volume (in^3)	Power (Amp)	Burn Time (min)	Measured Parameters			
									TPM	M	Cr(VI)	PSD
1	PA02B1X	HY80	Plasma Arc	45.00			600	2.33	X	X	X	
2	PA02B1	HY80	Plasma Arc	20.75	0.325	13.49	600	1.00	X	X	X	
3	PA05B1	HY80	Plasma Arc	19.50	0.32	12.48	500	1.50	X	X	X	
4	PA01B1	HY80	Plasma Arc	26.00	0.36	18.72	600	2.00	X	X	X	X
5	PA01B2	HY80	Plasma Arc	39.00	0.38	29.64	600	3.00	X	X	X	
6	PA03B1	HY80	Plasma Arc	48.00	0.295	28.32	600	1.78	X	X	X	X
7	PA02B2	HY80	Plasma Arc	40.37	0.325	26.24	600	2.00	X	X	X	
8	PA06B1	HY80	Plasma Arc	39.81	0.305	24.28	600	1.52	X	X	X	
9	PA05B2	HY80	Plasma Arc	39.00	0.355	27.69	500	3.00	X	X	X	
10	PA01B3	HY80	Plasma Arc	25.19	0.36	18.14	600	2.00	X	X	X	
11	PA04B1	HY80	Plasma Arc	38.25	0.275	21.04	370	3.00	X	X	X	X
12	PA04B2	HY80	Plasma Arc	41.37	0.275	22.75	360	3.25	X	X	X	
13	PA03B2	HY80	Plasma Arc	39.00	0.30	23.40	600	1.50	X	X	X	X
14	PA08B1	HY80	Plasma Arc	38.87	0.27	20.99	600	1.50	X	X	X	
15	PA07B1	HY80	Plasma Arc	38.50	0.255	19.64	420	3.00	X	X	X	
21	PA09C1	HY80	Plasma Arc	26.75	0.27	14.45	600	1.00	X	X	X	
22	PA09C2	HY80	Plasma Arc	26.75	0.27	14.45	600	1.00	X	X	X	X
23	PA10C1	HY80	Plasma Arc	32.50	0.28	18.20	360	2.50	X	X	X	
24	PA10C2	HY80	Plasma Arc	25.00	0.285	14.25	360	2.50	X	X	X	
30	PA01B3	HY80	Plasma Arc	31.87	0.415	26.45	600	2.50	X	X	X	
31	PA02B3	HY80	Plasma Arc	41.62	0.32	26.64	600	2.10	X	X	X	
32	PA05B3	HY80	Plasma Arc	33.19	0.36	23.90	500	2.58	X	X	X	
33	PA12B1	HY80	Plasma Arc	43.75	0.275	24.06	500	2.00	X	X	X	
34	PA03B3	HY80	Plasma Arc	41.94	0.29	24.33	600	1.55	X	X	X	
35	PA13C1	HY80	Plasma Arc	37.50	0.265	19.88	600	1.37	X	X	X	
36	PA14C1	HY80	Plasma Arc	27.25	0.38	20.71	600	2.10	X	X	X	

PH - Pressue Hull; TPM - Total Particulate Matter ; *M - Metals; Cr(VI) - Hexavalent Chromium; PSD - Particle Size Distribution; Samples IDs that contain B had no coatings other than the residue of the mill primer; Samples IDs that contain C were submarine hull sections which had interior paint and exterior paint with some adhesive/tile residue; Plate Thickness – 2 inches.*

Table 3: Emission Factors for Oxy-MAPP Cutting and Arc Gouging – PSNS Sampling

ID	TPM	Cr(VI), mg/Kg		Be	V	Cr	Fe	Mn	Ni	Co	Cu	Zn	As	Mo	Cd	Sb	Pb
	g/kg	Low	High	mg/Kg													
11	14.2	0.20	0.24	0.000	0.30	184.6	8798	31.9	717	1.56	46.7	10.1	7.0	298	0.31	63.9	3.12
12	18.5	0.05	0.27	0.000	0.33	225.9	10117	37.4	884	2.34	54.5	15.6	8.6	444	0.44	10.1	1.56
12X	14.5	0.43	1.05	0.000	0.34	164.4	7998	29.6	618	1.56	38.9	14.0	4.7	252	0.30	0.8	1.56
21	13.8	0.73	3.96	0.000	0.26	177.6	8453	30.4	711	1.56	38.9	8.6	5.5	305	0.32	0.8	1.56
1	28.3	0.10	0.14	0.012	0.62	278.1	16392	104.4	1192	5.45	264.9	103.6	21.0	469	0.76	7.0	5.45
2	28.0	0.03	0.14	0.009	0.45	278.1	16779	81.0	1207	7.01	194.7	81.8	17.9	378	0.48	7.8	2.34
3	26.3	ND	0.14	0.013	0.64	253.2	13892	84.9	989	3.89	218.1	111.4	15.6	373	1.32	34.3	5.45
4	18.5	0.05	0.07	0.000	0.35	188.5	11102	48.3	738	4.67	124.6	46.7	12.5	216	0.30	14.0	16.36
5	46.4	0.17	0.23	0.012	1.25	420.7	31420	137.9	1748	10.13	62.3	13.2	8.6	697	0.68	1.6	0.78
6	52.2	0.13	0.97	0.013	1.01	433.9	31909	133.2	1952	11.68	77.9	14.0	9.3	802	0.78	36.6	2.34
7	17.8	0.02	0.12	0.000	0.27	155.0	10055	38.9	602	4.67	46.7	70.1	8.6	238	0.45	72.4	7.01
9	10.2	0.19	0.62	0.000	0.31	123.1	6235	47.5	492	3.12	31.2	7.8	3.9	242	0.29	0.8	2.34
10	13.9	0.94	2.14	0.000	0.37	160.5	8674	86.5	647	3.89	46.7	10.1	6.2	305	0.37	127.0	17.92
16	19.6	0.04	0.78	0.000	3.66	15.6	7456	101.3	42	2.34	187.0	151.9	3.9	0	0.24	41.3	54.53
17	21.0	ND	0.03	0.000	3.12	18.7	8684	127.8	36	4.67	560.9	21.0	7.8	0	0.12	172.2	160.47
13	61.9	8.86	10.5	0.033	1.71	507.1	40267	182.3	2041	7.79	296.0	25.7	7.0	650	0.65	1.6	2.34
15	47.1	3.56	7.03	0.000	0.86	380.9	30649	157.4	1534	4.67	202.5	28.0	5.5	234	0.64	113.7	15.58

Be - Beryllium; V - Vanadium; Cr - Chromium; Fe - Ferrous; Mn - Manganese; Ni - Nickel; Co - Cobalt; Cu - Copper; Zn - Zinc; As - Arsenic; Mo - Molybdenum; Cd - Cadmium; Sb - Antimony; Pb - Lead
Note: Refer to Table 1 for Sample ID description.

Table 4: Emission Factors for Oxy-MAPP and Plasma Arc Cutting – Battelle Sampling

ID	TPM	Cr(VI)	Be	V	Cr	Fe	Mn	Ni	Co	Cu	Zn	Mo	Cd	Sb	Pb
	g/Kg	mg/Kg													
1	0.00	0.00	0.000	0.000	0.0	0	0.0	0	0.00	0.0	0.00	0.0	0.000	0.00	0.000
2	37.09	1.24	0.000	0.000	323.9	14802	265.1	1264	0.00	246.8	15.80	198.6	0.098	0.00	0.000
3	6.63	0.18	0.000	0.000	77.3	3873	61.9	282	0.00	61.4	13.41	49.8	0.000	0.00	0.000
4	5.41	0.11	0.000	0.000	48.5	2764	47.6	256	0.00	80.6	12.84	62.3	0.000	0.00	0.000
5	10.76	0.12	0.000	0.000	66.4	3634	56.5	357	0.00	79.6	16.79	60.9	0.193	0.00	0.000
6	8.06	0.26	0.000	0.000	63.8	3443	50.4	311	0.00	66.7	10.89	57.5	0.162	0.00	0.000
7	22.02	0.31	0.000	0.000	126.2	6183	115.5	455	0.00	83.6	6.78	59.4	0.369	0.00	0.000
8	17.34	0.22	0.254	0.000	169.8	7861	116.2	728	6.17	125.9	17.05	104.5	0.653	0.00	0.000
9	4.52	0.11	0.000	0.000	39.2	2160	37.2	152	0.00	32.8	12.21	24.0	0.000	0.00	0.000
10	0.00	0.00	0.000	0.000	0.0	0	0.0	0	0.00	0.0	0.00	0.0	0.000	0.00	0.000
11	0.63	0.01	0.000	0.000	13.8	439	9.1	44	0.00	12.6	14.53	7.6	0.000	0.00	0.000
12	0.62	0.01	0.000	0.000	8.6	250	6.8	27	0.00	9.8	13.94	5.2	0.000	0.00	0.000
13	21.76	0.46	0.000	0.000	158.5	7622	117.2	708	0.00	128.8	10.01	98.2	0.527	0.00	0.000
14	29.75	1.03	0.000	0.000	275.7	11267	244.3	997	4.91	191.0	15.11	121.4	0.839	0.00	0.000
15	4.13	0.06	0.000	0.000	42.8	2347	40.1	172	0.00	39.5	15.70	29.2	0.000	0.00	0.000
21	12.44	0.03	0.000	0.000	112.2	6890	89.6	496	0.00	58.5	17.13	84.9	0.311	0.00	13.414
22	11.79	0.04	0.000	0.000	94.6	5858	74.8	419	0.00	40.1	15.56	69.0	0.000	0.00	11.972
23	2.28	0.01	0.000	0.000	26.6	1476	29.1	101	0.00	21.6	17.10	17.2	0.000	0.00	15.345
24	4.38	0.02	0.000	0.000	34.4	1869	44.1	146	0.00	34.7	87.62	19.6	0.000	0.00	17.221
30	3.38	0.10	0.000	0.059	27.6	1836	32.6	160	0.48	41.7	16.25	31.2	0.085	0.81	0.721
31	14.78	0.45	0.000	0.316	138.6	9512	158.9	510	1.53	109.1	14.67	79.1	0.127	1.49	0.902
32	3.05	0.10	0.000	0.047	22.9	1473	29.4	137	0.41	38.3	22.07	26.1	0.044	0.95	1.019
33	5.64	0.19	0.000	0.206	88.1	6538	97.4	446	1.35	103.7	22.29	82.8	0.235	3.77	2.689
34	17.05	0.45	0.000	0.240	100.5	7759	106.7	600	1.79	128.4	17.80	107.5	0.747	2.70	0.783
35	13.92	0.02	0.000	0.087	52.9	3877	57.7	303	1.57	32.4	49.16	54.5	0.105	3.36	20.584
36	21.04	0.03	0.000	0.231	93.8	7238	121.2	401	2.16	39.5	41.23	70.5	0.126	7.74	20.713

Be - Beryllium; V - Vanadium; Cr - Chromium; Fe - Ferrous; Mn - Manganese; Ni - Nickel; Co - Cobalt; Cu - Copper; Zn - Zinc; As - Arsenic; Mo - Molybdenum; Cd - Cadmium; Sb - Antimony; Pb – Lead
Note: Refer to Table 2 for Sample ID description.

Table 5: Particle Size Distribution for Oxy-MAPP and AHPA Cutting Processes

Particle Size	Cumulative Mass Fraction of Particles Less than the Size Indicated								
(micron)	ID 2	ID 4	ID 17	ID 21	PA01B1	PA03B1	PA04B1	PA03B2	PA09C2
0.05	0.136	0.192	0.066	0.168	0.183	0.150	0.086	0.039	0.146
0.1	0.184	0.347	0.380	0.274	0.265	0.240	0.112	0.136	0.263
0.2	0.271	0.422	0.486	0.323	0.282	0.263	0.132	0.177	0.300
0.4	0.343	0.500	0.767	0.355	0.303	0.299	0.143	0.228	0.332
0.8	0.385	0.552	0.833	0.387	0.338	0.339	0.186	0.289	0.363
1.6	0.532	0.697	0.880	0.512	0.426	0.424	0.275	0.409	0.446
3.2	0.838	0.929	0.925	0.823	0.557	0.578	0.428	0.702	0.671
6.4	0.910	0.993	0.962	0.910	0.797	0.804	0.803	0.902	0.911
12.5	0.932	1.000	0.977	0.913	0.831	0.824	1.000	1.000	1.000
25	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Note: Refer to previous tables for sample identification.									